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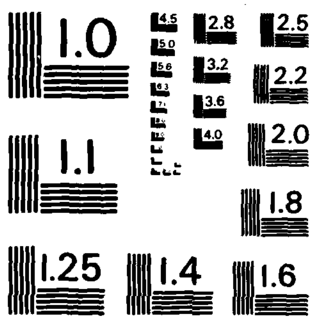

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ANNUAL TECHNICAL REPORT

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MICROWAVE SEMICONDUCTOR RESEARCH -
MATERIALS, DEVICES AND CIRCUITS

May 1, 1984 - April 30, 1985

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This program covers the growth and assessment of gallium arsenide and related compounds and alloys for use in microwave, millimeter wave, and optical devices. It also covers the processing of the material into devices, the testing of the devices, and the theoretical modeling of carrier transport in these devices. Both molecular beam epitaxy (MBE) and organometallic vapor phase epitaxy (OMVPE) are used for growth. The following specific tasks are pursued:

Task 1 Develop an improved understanding of the role of the substrate and the growth parameters on the quality of device structures on GaAs and related materials grown by OMVPE.

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Task 2 Investigate the frequency and power limits of power FET devices employing a two-dimensional electron gas in the channel.

Task 3 Produce semiconductor light emitters capable of high speed amplitude modulation.

Task 4 Investigate and improve heterojunction structures for transistor applications.

Task 5 Develop high speed receivers for optical communication using optical field effect transistors and large area epitaxial photoconductive detectors.

Task 6 Model and construct components and subsystems which can be useful as transmitters in optical communication systems.

Task 7 Develop advanced design techniques for microwave GaAs FET amplifiers.

Task 8 Improve direct method of broad band circuit design.

Task 9 Use optical excitation to study carrier dynamics in compound semiconductors.

Task 10 Explore transient carrier transport in small III-V devices in boundary limited domain.

WORK STATEMENT

TASK 1 Develop an improved understanding of the role of the substrate and the growth parameters on the quality of device structures on GaAs and related materials grown by OMVPE.

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TASK 1 GROWTH AND CHARACTERIZATION OF GaAs FOR HIGH PERFORMANCE MICROWAVE DEVICES

L.F. Eastman and D.W. Woodard

OBJECTIVE

The overall program objective is to develop an improved understanding of the role of the substrate and the growth parameters on the quality of device structures on GaAs and related materials grown by Organometallic Vapor Phase Epitaxy (OMVPE).

APPROACH

The approach to improve device quality materials grown by OMVPE centers around a fast feedback loop from data obtained from various characterization techniques and the actual growth parameters used during the deposition of epitaxial films. During this investigation an optimized process for various device structures of interest will be obtained using characterization data from low temperature photoluminescence (PL), deep level transient spectroscopy (DLTS), Hall and CV measurements, and other appropriate techniques. For example, a detailed understanding of the effects of the growth parameters on the optical and electronic properties of a GaAs/AlGaAs heterostructure will result in improved performance of some of the electron devices fabricated in other tasks in the JSEP program.

PROGRESS

During the first year of this reporting period, the technique of conductance DLTS was automated and made more sensitive. Sophisticated analysis routines (modified Boxcar, Fast Fourier Transform and Method of Moments), were developed and applied to the DLTS data in order to identify deep levels in GaAs MESFETs. Many levels found have never been reported. Conductance DLTS theory was developed to enable the calculation of trap densities thus obtaining trap density profiles in the active region of the FETs. The conductance DLTS experiment was also extended to temperatures as low as $15^{o}K$ to observe traps with smaller activation energies than previously possible. Electron traps and hole traps with energies less than 50 meV were observed for the first time in GaAs. Some of these levels can possibly be identified by comparison of the DLTS and

photoluminescence data.

MESFETs fabricated from ion-implanted, MBE, VPE and LPE material were analyzed by obtaining trap profiles to enable determination of the effects of deep levels present on the device's performance. Looping, dc drift and light sensitivity of the I-V characteristics were correlated with large densities of deep levels located at the surface and at the active region - buffer layer (or substrate) interface. Trap populations were shown to be deleterious to power applications of the devices by causing premature breakdown through impact ionization processes. It was seen that buffer layers, while decreasing the density of traps coming from the substrate, were not sufficiently opaque to eliminate them. By knowing the locations and energies of the traps in the channel, the contribution of specific deep levels to microwave performance has been calculated. Traps with energies between .07 and .2 eV contribute to the minimum excess noise figure between 1 and 80 GHz. Deeper traps, depending on their emission rates, can affect the performance of the devices down to the dc characteristics.

Electron and hole traps introduced as a result of Si_3N_4 surface passivation have been identified and profiled. Nitride capping and annealing of ion implanted material was found to introduce various low energy surface traps. The effects of these traps on microwave performance were calculated.

By the start of the second year of this reporting period Cornell had successfully designed and constructed a variable pressure OMVPE reactor for the growth of epitaxial III-V compound semiconductors. Since then the research effort at Cornell has centered around the OMVPE growth and characterization of GaAs, AlGaAs and their heterostructures. This effort has led to the obtainment of high purity n-type GaAs (μ_n at 77 K in excess of 93,000 cm^2/v-s) an optimized As/Ga ratio of 72 and a substrate temperature of 650^{o}C. In addition, the effects of in-situ substrate etching and arsine cracking on high purity GaAs were determined during this study. Low temperature photoluminescence data showing fine exciton structure at GaAs's band edge has been correlated with the growth parameters including substrate temperature and the As/Ga ratio. In addition, DLTS measurements indicate the dominant residual deep center, the electron trap EL2, decreases with lower As/Ga ratios. The traps

concentration has been reduced to less than $10^{13}cm^{-3}$ at As/Ga ratios less than 30. Finally, the behavior of the electron mobility, the carrier concentration and the photoluminescence efficiency for undoped GaAs films with the primary growth parameters has been determined. For example, under suitable growth conditions, thick (around 10 microns) semi-insulation GaAs layers may be reproducably obtained and incorporated buffer layers on semi-insulating substrates for a variety of device structures.

The growth of AlGaAs films was investigated over the full range of alloy compositions with several As/(Ga+Al) ratios and over a temperature range from 550-800^{o}C. It was observed that the optical properties of these films were severely degraded due to the incorporation of oxygen from the growth ambient. In an effort to reduce oxygen contamination, a new oxygen gettering scheme was applied to the arsine gas, the suspected source of the contamination. The radiative yield of the $Al_{0.25}Ga_{0.75}As$ was improved by a factor of 5 as a result of the removal of moisture from the arsine gas. The use of this oxygen gettering system has resulted in narrow linewidths (less than 5 meV) in low temperature photoluminescence spectra of $Al_{.26}Ga_{.24}As$ film grown at relatively low temperatures (around 700^{o}C). These linewidths have been compared with theoretical predictions by Schubert et al. ("Alloy broadening in photoluminescence spectra of $Al_xGa_{1-x}As$", Physical Review B, Vol. 30, No. 2, p. 813, July 1984) and found to be in excellent agreement over the entire range of compositions corresponding to direct bandgap alloys. These calculated linewidths consider broadening from random Ga and Al distributions on the group III sublattice while no impurity related broadening effects are considered. Hence, even when ultra high purity films of AlGaAs are obtained, linewidths of low temperature PL will not be improved over the films presently grown.

During the third year of the program improved sources of trimethylgallium (TMG) yielded electron mobilities as high as 130,000 $cm^2v^{-1}s^{-1}$. This was obtained at a reduced V/III ratio of 50 as a result of lesser acceptor impurity incorporation. It was also determined that the residual impurity concentration in the $Al_xGa_{1-x}As$ could not be reduced to levels below $10^{16}cm^{-3}$ with the existing trimethylaluminum (TMA) source. This problem, which was orignally attributed to impurities in the TMA

source, have now been found to result from high levels of carbon incorporated by the inherent reaction mechanism when using the methyl source (N. Kobayashi and T. Fukui, "Improved 2DEG Mobility in Selectively Doped GaAs/N-AlGaAs Grown by MOVPE Using Triethyl Organometallic Compounds", Electron. Lett., Vol. 20, No. 21, p. 887, Oct. 1984). Consequently, use of the triethylaluminum (TEA) source was investigated. The results show mobilities of two dimensional electron gas (2DEG) structures as high as 52,000 $cm^2 v^{-1} s^{-1}$ with the limit being attributed to the available purity of the TEA source. The $Al_xGa_{1-x}As$ grown with this source shows broad low temperature photoluminescence spectra and a background electron concentration of $n \sim 1 \times 10^{17} cm^{-3}$. Subsequent investigations will include different TEA source vendors (e.g., Texas Alkyl) in order to further improve the 2DEG mobility.

The heterojunction abruptness in GaAs/AlGaAs structures is critical to several device applications including modulation doped FET's and quantum well lasers. Experiments related to heterojuction interface abruptness in the third year yielded $GaAs/Al_xGa_{1-x}As$ quantum wells as thin as 40 Å. This limit was found to be essentially independent of growth parameters including stopping growth at the interfaces. The past years effort has been dedicated towards an understanding of the phenomenon. It was found taht interface grading as determined by transmission electron microscopy was due to pressure transients during value switching in the reactor. An extensive modification was made on the apparatus in order to monitor these pressure transients and eliminate them by a pressure balancing scheme. In addition, new gas switching manifolds were designed and constructed in order to eliminate dead space in the source lines and reduce reactant transport times. The results, as determined by low temperature photoluminescence (LT PL) and transmission electron microscopy (TEM), indicate quantum well heterostructures are now possible, for the first time, less than 20 Å thick showing optical activity and interfaces less than 10 Å (TEM resolution limit) in a low pressure OMVPE reactor.

Further work was dedicated towards gas flow dynamics inside the growth chamber. Modifications here have eliminated the commonly observed recirculation and convection currents improving uniformity ($\pm$ 8% thickness over 5 1/2 $in.^2$) and removing low levels of background Al inside thin GaAs quantum wells. The latter was previously accomplished only through growth

stoppage at the interface. These results will allow us to further improve the quality of heterostructure device materials for microwave applications.

Finally, a series of experiments on $Ga_xIn_{1-x}P$ material was conducted. This material can be conveniently lattice matched to GaAs substrates and offers an interesting and potentially very useful alternative to $Al_xGa_{1-x}As$ for use in spacer and/or wide bandgap emitter layers in 2DEG FET's and bipolar heterojunction transistors for microwave applications. Lattice matched $Ga_xIn_{1-x}P$ was grown on GaAs and AlAs buffer layers and showed strong LT PL as well as at room temperature. Quantum wells in $Al_xGa_{1-x}As/Ga_yIn_{1-y}P$ materials were grown with $Ga_yIn_{1-y}P$ active layers as thin as 40 Å. These structures also showed strong PL. Further work will be aimed at applying this material towards device structures.

DEGREES

None

PUBLICATIONS

1. "Graded Band-Gap AlGaAs Solar Cells Grown by Organometallic Vapor Phase Epitaxy", D.K. Wagner and J.R. Shealy, Proc. Photovoltaics Specialists Conf., Orlando, FL (May 1-4, 1984).
2. "Graded Band-Gap p/n AlGaAs Solar Cells Grown by Organometallic Vapor Phase Epitaxy", D.K. Wagner and J.R. Shealy, Appl. Phys. Lett., 45 (2) 162-164 (July 1984).
3. "Optical Devices by MOCVD", C. Schaus, PROSUS, Ithaca, NY (Oct. 11-12,1984).
4. "High External Efficiency (36%) 5-Micron Mesa Isolated GaAs Quantum Well Laser by Organometallic Vapor Phase Epitaxy", D.F. Welch, C..F. Schaus and J.R. Shealy, Appl. Phys. Lett., 46 (2) 121-123 (Jan. 1985).

TASK 2 FUNDAMENTAL STUDY OF THE PERFORMANCE LIMITS OF HIGH FREQUENCY GaAs FET's

L.F. Eastman, D.W. Woodard and S.D. Mukherjee

OBJECTIVE

The objective of this task is to investigate the frequency and power limits of power FET devices employing a two-dimensional electron gas in the channel.

APPROACH

The approach being taken is to experimentally evaluate the performance of power FET devices made with $Al_xGa_{1-x}As$-GaAs modulation doped materials structures specially optimized for high sheet concentration and high mobility.

PROGRESS

A new modulation doped structure has been grown with simultaneous high sheet concentration ($n_s = 1 \times 10^{12}$), high 77°K mobility (119,000 cm^2/v-sec), and freedom from light sensitivity. It consists of a 1 micron GaAs buffer layer followed by a 50 Å spacer of undoped $Al_{.45}Ga_{.55}As$, a 260 Å Si doped $Al_{.2}Ga_{.8}As$ layer with $N_D = 5 \times 10^{18}/cm^3$, and a 260 Å undoped GaAs capping layer. The high Al fraction (.45) in the spacer assured a high barrier for prevention of real space transfer into the $Al_xGa_{1-x}As$.

The low Al fraction (0.20) in the doped region avoided the light sensitivity problems associated with deep levels in $Al_xGa_{1-x}As$ which occur when $x \geq 0.24$. As yet, devices have not been evaluated with this material, but work is in progress to further increase the sheet concentration by development of double heterostructure material.

DEGREES

C. Lowe, Ph.D., August 1984, "A Study of Breakdown Voltage for Gallium Arsenide Power Transistors with Gatelengths in the Submicron Range".

PUBLICATIONS

1. "An Optimized HEMT Structure with an $Al_{.45}Ga_{.55}As$ Spacer and an $Al_{.2}Ga_{.80}As$ Doped Region", J.C. Huang, G.W. Wicks, A.R. Calawa and L.F. Eastman, submitted to Electronic Letters.

TASK 3 MBE GROWN-LATTICE-MATCHED HETEROJUNCTION FOR IMPROVED TRANSISTORS

L.F. Eastman and G.W. Wicks

OBJECTIVE

The objective of this task is the continued investigation and improvement of heterojunction structures for transistor applications. During this year, two particular tasks were emphasized, namely increasing the sheet conductivity of the two dimensional electron gas (2DEG) in an AlGaAs/GaAs modulation doped field effect transistor (MODFET) and optimizing the injection efficiency (γ) of the AlGaAs/GaAs heterojunction bipolar transistor (HBT).

APPROACH

In attempting to maximize the sheet conductivity of the 2DEG in a MODFET, two of its characteristics must be dealt with, the sheet concentration of the 2DEG (n_s) and its mobility (μ). In conventional MODFET structures, these two characteristics are typically varied by varying the thickness of the undoped spacer layer. In this project, n_s and μ were manipulated by varying the composition of the spacer layer. Structures with differing spacer layer compositions were grown by MBE and characterized by Hall measurements.

The first problem encountered in attempting to maximize γ in an AlGaAs/GaAs HBT is measure it directly. In the past γ could only be inferred from the current gain of the transistor and making some assumptions about the base transport factor and collector efficiency. In this project, a novel optical technique was developed which allowed γ to be measured directly on heterojunction diodes by comparing the intensities of the GaAs and AlGaAs electroluminescence when the diode was forward biased. When γ was measured on test structures it was found to be drastically effected by unintentional movement of Be from the p-type GaAs into the AlGaAs, as discussed in the next section. Therefore, movement of Be during MBE was also investigated. This investigation was accomplished by growing test structures doped with Be and examining the Be profiles with SIMS.

PROGRESS

In conventional MODFET's, n_s and μ_{77K} are typically 0.8-1.0 x 10^{12} cm^{-2} and 50,000-60,000 cm^2/v-sec respectively. By utilizing undoped spacer layers consisting of $Al_{.45}Ga_{.55}As$, rather than the conventional $Al_{.25}Ga_{.75}As$, we have

obtained MODFET structures with $n_s = 1.0\text{-}1.2 \times 10^{12} cm^{-2}$ and μ_{77K} = 100,000-120,000 cm^2/v-sec. To our knowledge, these are the highest reported sheet conductivities of single 2DEG's. In addition to the high sheet conductivity, another expected advantage of this structure is that it confines the 2DEG utilizing the maximum conduction band discontinuity, ΔE_c, available in the AlGaAs/GaAs material system. Thus, real space transfer of energetic electrons will occur at higher energies, allowing higher electron velocities in the channels of these MODFET's.

The injection efficiencies measured in what were intended to be abrupt n-AlGaAs/p-GaAs heterojunctions were 30-40% instead of the theoretically expected 98-99%. The reason for this discrepancy was found to be unintentional movement of beryllium from the p-GaAs into the AlGaAs, resulting in an n-AlGaAs/p-AlGaAs/p-GaAs structure rather than the intended one. Subsequently, it was found that by stopping the Be doping 200 Å before the heterojunction, the Be did not penetrate into the AlGaAs, resulting in theoretical values of injection efficiency.

Beryllium diffusion was found to occur by two mechanisms, rapid interstitial diffusion at high incident fluxes of Be and substitutional-interstitial diffusion for doping concentrations below $10^{19} cm^{-3}$. Diffusion coefficients were found to be about $10^{-9} cm^2$/sec and about $10^{-14} cm^2$/sec, respectively.

DEGREES

Hao Lee, Ph.D., January 1985, "Growth of Optimized GaAs/(Al,Ga)As Modulation Doped Heterostructures by Molecular Beam Epitaxy for FET Applications".

PUBLICATIONS

1. "Optimized GaAs/(Al,Ga)As Modulation Doped Heterostructures", H. Lee, W.J. Schaff, G.W. Wicks, L.F. Eastman and A.R. Calawa, 11th Int. Symp. on GaAs and Related Cpds, Biarritz, France (Sept. 26-28, 1984).
2. "Two New GaAs/(Al,Ga)As Modulation Doped Heterostructures for FET Applications", H. Lee, W.J. Schaff, G.W. Wicks, L.F. Eastman and A.R. Calawa, Workshop on Selectively Doped Heterostructure Materials, Devices and Circuits, Santa Barbara, CA (Dec. 3-7, 1984).

TASK 4 HIGH SPEED AMPLITUDE MODULATION OF SEMICONDUCTOR LASERS AND LIGHT EMITTING DIODES

L.F. Eastman and G.W. Wicks

OBJECTIVE

The objective is to produce semiconductor light emitters capable of high speed amplitude modulation.

APPROACH

The problem of high speed modulation of semiconductor light emitters has been approached by other researchers by modulating the drive current of conventional double heterostructure (DH) lasers. The approach used in this task is threefold. First, modulation of high quality quantum well (QW) lasers is being investigated since it is expected theoretically that QW lasers are faster than DH lasers. Second, under investigation is a novel, three terminal structure in which a high electric field can be imposed across the quantum well active region, thereby quenching the light emission. Third, research is being conducted on a scheme in which a semiconductor laser operating continuously can be integrated with an optical modulator.

PROGRESS

1) An experiment apparatus has been assembled for modulating and testing lasers and LED's in the 1-26 GHz frequency range.
2) GRINSCH lasers with 250 Å quantum wells were modulated at frequencies up to 4 GHz.
3) A series of quantum lasers have been grown by MBE, fabricated and dc tested. The dc thresholds and differential quantum efficiencies are at the state of the art. High frequency testing is forthcoming.
4) A three terminal LED has been successfully fabricated. The device turns on with 2 mA of drive current. The optical output can be modulated with 1 volt of gate bias. High frequency measurements have not yet been made.
5) In order to construct a quantum well laser (operated continuously) which would be integrated with an optical modulator, it would be convenient to be able to disorder superlattices with implantation or diffusion. This would allow lateral index changes to be constructed for waveguides and diffraction gratings. Superlattices grown by MBE were implanted with

several different elements, annealed, and characterized by cross sectional transmission electron microscopy and Raman spectroscopy. Among other findings, it was determined that light mass implants, e.g., beryllium, did not disorder the superlattices, however heavy mass implants, e.g., selenium, resulted in complete disorder.

DEGREES

Eric Elias, M.S., August 1985, "A Gate Modulated Quantum Well Light Emitting Diode".

PUBLICATIONS

"Defect Structure and Intermixing of Ion-Implanted $Al_xGa_{1-x}As/GaAs$ Superlattices", J. Ralston, G.W. Wicks and L.F. Eastman, to be published Appl. Phys. Lett. (1985).

TASK 5 HIGH SPEED RECEIVERS FOR OPTICAL COMMUNICATIONS

J.M. Ballantyne

OBJECTIVE

The objectives of this program are to develop large area photoconductive detectors which are suitable for monolithic integration with preamplifiers, and to develop MOCVD growth techniques of materials suitable for monolithic optoelectronic subsystems. Included in these objectives are the analysis of fast photoconductive detectors so that the details of their operation at high frequencies are understood. This includes the development of suitable circuit models to describe their operation and the development of design strategies which allow prediction of properties such as speed, gain and noise of large area photoconductors monolithically integrated with preamplifiers. Prototype photodetectors and monolithically integrated receivers are fabricated and performance evaluated and compared with predictions.

APPROACH AND PROGRESS

Detectors and Amplifiers

Some "normallly-off" photoconductive detectors were fabricated in order to decrease the quiescent current of the devices. These were found to have unusual I-V characteristics. Theoretical analysis indicates a space charge limited current flow is possible. More abrupt interfaces between the active layer and semi-insulating substrate are needed to reduce leakage currents. Current devices were fabricated in standard MESFET layers; however, more lightly doped layers are needed to better control the pinch-off mechanism and are scheduled to be grown by MOCVD.

Previous work on interdigitated detector optimization concentrated on finding optimum "finger" sizes to maximize device active area while minimizing contact resistance. This led to a relatively simple result. More complicated analysis for maximizing the gain, bandwidth, and gain bandwidth product in terms of finger length, width, and spacing between fingers was undertaken, since these are more directly applicable figures of merit. No simple (analytical) result was obtained in this case. Programs were written that obtain optimum detector dimensions given material and ohmic contact parameters by using an exhaustive search to numerically obtain solutions to the optimization problem.

In conjunction with a General Electric project, a monolithically integrated detector and amplifier were designed as part of an optical demultiplexing circuit to be fabricated by a commercial GaAs ion-implantation depletion mode MESFET technology. These will be to the best of our knowledge the first ion-implanted detectors studied.

MOCVD Growth of Detector Layers

Further work on the growth of GaInAs and InP have been carried out after a new source of trimethylindium was installed to replace triethylindium. Undoped materials have been grown and state-of-the-art results were obtained. The best liquid nitrogen mobilities for InP and GaInAs are 130,000 and 80,000 respectively. They represent the highest values ever obtained in MOCVD by TMI and compare well with the results achieved by Thomson-CSF. The minimum 4K photoluminescence exciton linewidth is 2.6 meV in GaInAs, also a record for the material grown by MOCVD. Lattice mismatch can be reproducibly controlled at less than 0.04%. Most important of all the interface between InP and GaInAs is smooth and abrupt enough to enable the formation of a two-dimensional electron gas, which has been confirmed by the Shubnikov-de Haas effect at liquid helium temperatures. This important result shows that high electron mobility transistors can be fabricated from materials grown in our MOCVD system. The high quality of the GaInAs layers obtained removes one major obstacle in the fabrication of optical detectors suitable for optical fiber communication purposes. Together with good interfaces between InP and GaInAs, these high quality materials seem to offer a very promising base for the development of integrated detectors and amplifiers for 1.3 and 1.55 micron lightwaves.

DEGREES

None

PUBLICATIONS

1. L.D. Zhu, K.T. Chan, D.K. Wagner and J.M. Ballantyne, "A Photoluminesence Study of the Growth of InP by Metalorganic Chemical Vapor Deposition", J. Appl. Phys., 57, 5486 (1985).
2. K.T. Chan, L.D. Zhu and J.M. Ballantyne, "Growth of High Quality GaInAs on InP Buffer Layers by Metalorganic Chemical Vapor Deposition", Appl.

Phys. Lett., 47, 44 (1985).

3. L.D. Zhu, K.T. Chan and J.M. Ballantyne, "Very High Mobility InP Grown by Low Pressure Metalorganic Vapor Phase Epitaxy Using Solid Trimethylindium Source", Appl. Phys. Lett., 47, 47 (1985).

4. L.D. Zhu, K.T. Chan and J.M. Ballantyne, "MOCVD Growth and Characterization of High Quality InP", J. Cryst. Growth (to be published).

5. L.D. Zhu, P.E. Sulewski, K.T. Chan, K. Muro, J.M. Ballantyne and A.J. Sievers, "Two-dimensional Electron Gas in InGaAs/InP Heterojunctions Grown by Atmospheric Pressure Metalorganic Chemical Vapor Deposition", J. Appl. Phys. (to be published, Oct. 15, 1985).

TASK 6 SPECTRAL AND DYNAMIC CHARACTERISTICS OF SEMICONDUCTOR MATERIALS AND STRUCTURES

C.L. Tang

OBJECTIVE

The main objective of the program is to study the relaxation dynamics and the photoluminescence properties of hot electrons in GaAs and related structures, such as GaAs/AlGaAs multiple quantum well structures.

APPROACH

The basic approach to study the ultrafast dynamics of free carriers in semiconductors is to use the femtosecond and picosecond lasers and techniques developed in our laboratory over the years to photoexcite electrons into highly energetic states in the conduction band and then measure the relaxation of these carriers. Optical pumping is used to study the spectral characteristics of various semiconductor laser materials and structures.

PROGRESS

Ultrafast Relaxation Dynamics of Hot Carriers in Semiconductors

Our main efforts last year have been directed toward improving the time resolution of our femtosecond laser system used to study the ultrafast relaxation dynamics of hot carriers in semiconductors and developing the necessary theory to interpret the data obtained.

Using a recently developed technique, the pulse width of our system has been reduced from the 80-100 femtoseconds range down to approximately 40 fs for experimental purposes. This improvement of a factor of 2 is very important for studying the ultrafast relaxation processes in III-V compounds. Most of the intraband relaxation times, which limit the ultimate speed of electronic and optic devices based on such materials, are in the range of 30 to 100 fs. With the earlier lasers, the time resolution is marginal and the interpretation of the data is complicated and has to rely heavily on theory. The new laser system should now provide an unambiguous check of our earlier results and allow us to study other ultrafast processes.

On the theoretical side, a detailed theory of the transmission-correlation technique for measuring the ultrafast relaxation rates in materials is developed. In particular, a detailed analysis of the coherent-

artifact contribution to the transmission-correlation peak is carried out. The relevant scattering processes and rates for GaAs and related materials and quantum-wells have been calculated and compared with measured results.

DEGREES

D.J. Erskine, "Ultrafast relaxation phenomenon of photoexcited carriers in GaAs and related compounds", Ph.D., Physics, June 1984.

PUBLICATIONS

1. "Femtosecond studies of intraband relaxation in GaAs, AlGaAs, and GaAs/AlGaAs multiple quantum well structures", D.J. Erskine, A.J. Taylor, and C.L. Tang, Appl. Phys. Lett., Vol. 45, 54-56 (1984).
2. "Dynamic Burstein-Moss Shift in GaAs and GaAs/AlGaAs multiple quantum wells", D.J. Erskine, A.J. Taylor, and C.L. Tang, Appl. Phys. Lett., Vol. 45, 1209-1211 (1984).
3. "Ultrafast relaxation dynamics of photoexcited carriers in GaAs and related compounds", A.J. Taylor, D.J. Erskine, and C.L. Tang, J. Opt. Soc. Am. B, Vol. 2, 663-673 (April 1985).
4. "Widely tunable optical parametric oscillator using urea", M.J. Rosker and C.L. Tang, J. Opt. Soc. Am. B, Vol. 2, 691-696 (May 1985).

PROCEEDINGS, CONFERENCE PAPERS AND TALKS

1. "Femtosecond studies of intraband relaxation of semiconductors and molecules", A.J. Taylor, D.J. Erskine, and C.L. Tang, Proc. of IV Topical Meeting on Ultrafast Phenomena (Springer Verlag, Sept. 1984).
2. "Femtosecond studies of intraband relaxation processes in semiconductors", invited talk, NSF US-Japan Bilateral Seminar on Quantum Electronics, Nara, Japan, August 31-Sept. 4, 1984.
3. "Femtosecond solid state measurements", invited talk, Opt. Soc. of Am. Annual Meeting, San Diego, CA, Nov., 1984.
4. "Femtosecond lasers and applications", invited seminar, Dept. of Phys., SUNY Binghamton, NY, Nov. 5, 1984.
5. "Femtosecond lasers", invited seminar, UC Berkeley, March 1985.
6. "A broadly tunable urea optical parametric oscillator", invited talk, Conf. on Lasers and Electro-optics, Baltimore, MD, May 1985.

TASK 7 CARRIER DYNAMICS IN COMPOUND SEMICONDUCTORS STUDIED WITH PICOSECOND OPTICAL EXCITATION

G.J. Wolga

OBJECTIVE

The objective of this research is to experimentally observe ballistic motion of hot carriers in GaAs using light scattering techniques.

APPROACH

Hot electrons will be injected into GaAs from an GaAs-AlGaAs heterostructure interface in a specially designed device. Sub-bandgap laser radiation will be directed into the device along the direction of motion of the electrons. The back-scattered laser radiation will be spectroscopically examined for a Doppler shifted component indicating a coherent velocity component in the electron flow. The magnitude of the Doppler shift will be a direct measure of the coherent velocity component while the spread in the scattered light spectrum can be correlated with elastic and inelastic collisions that degrade the coherent velocity component.

PROGRESS

1. A spectroscopic measurement system has been assembled and tested. It includes a tunable dye laser (8400-9000 A), liquid nitrogen optical dewar, double monochromator (optimized for the near infrared), photon counting apparatus with GaAs, optimized photomultiplier tube, and a current pulser for launching electrons in the experimental devices. Each of these is interfaced with a H.P. computer which controls the experiment. Amplitude modulation of the launched electron beam will permit phase-sensitive detection of the photon counted signal thereby further enhancing the S/N. Results of stray light measurements show a rejection ratio of 10^{11} at a spectral location of 25 A from the laser line. This rejection ratio is suitable for the signle particle light scattering experiments, while further enhancement using phase sensitive detection is possible.
2. The unique GaAs-AlGaAs heterostructure launchers have been processed on MBE grown material and mounted on special heat sinks. The heterostructure is grown on n^+ GaAs substrate. Processing includes thinning the substrate to less than 50 microns followed by metallization

leaving a 40 micron aperture for the light to enter the device and scattered light to be collected from the device.

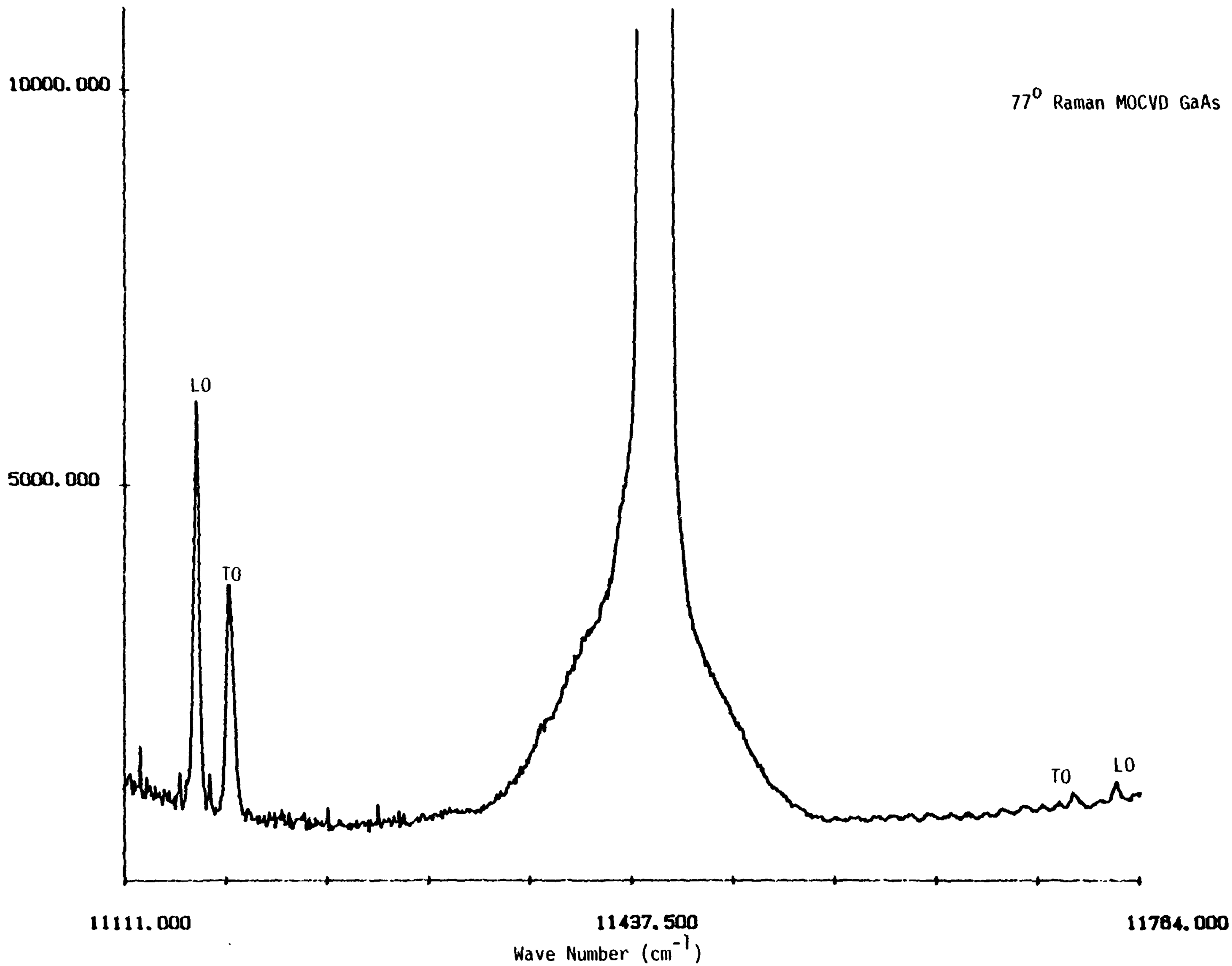
3. Using high purity semi-insulating GaAs grown by MOCVD, TO and LO phonon spectra have easily been observed. This establishes the ability of the measurement system to detect single particle (electron) photon scattering since the effective scattering cross section for optical phonons is comparable with electron scattering cross sections. (See accompanying figure).
4. Preliminary measurements suggest that single particle (electron) scattering has been observed centered on the Rayleigh (laser) line. This would be the thermal-diffuse Rayleigh-wing scattering not the Doppler shifted light scattering we wish to observe. However these results give further indication that our experimental sensitivity is satisfactory. Again the samples were high purity GaAs grown on insulating GaAs substrates by MOCVD. (See accompanying figure).

DEGREES

None

PUBLICATIONS

None


77° Raman MOCVD GaAs
10000.000
5000.000
LO
TO
TO
LO
11111.000
11437.500
11784.000
Wave Number (cm⁻¹)

TASK 8 ADVANCED DESIGN TECHNIQUES FOR MICROWAVE GaAs FET AMPLIFIERS

W.H. Ku

OBJECTIVE

The primary objectives of this continuing research program are to derive fundamental device/circuit performance limitations for GaAs metal-semiconductor FETs (MESFETs) and for the higher electron mobility transistor (HEMT), and to develop advanced and integrated analytical and computer-aided design (CAD) techniques for the synthesis and design of GaAs MESFET/HEMT amplifiers, mixers and VCO's leading to monolithic microwave integrated circuits (MMICs) and subsystems. A secondary objective of this research program is to fabricate prototype GaAs MESFET/HEMT amplifiers and circuits in microstrip and monolithic realizations using state-of-the-art submicron gate-length MESFET/HEMT's to verify the integrated design approach developed in the main portion of this 6.1 JSEP program.

It is anticipated that, because of the fundamental nature of this proposed research, the results obtained should have a direct and significant impact on various DOD programs involving ultra-wideband GaAs MESFET/HEMT amplifiers and MMICs which are directed to ECM and EW system applications and monolithic transceiver modules for phased array applications.

APPROACH

Tremendous progress has been made over the past several years in low-noise and power GaAs MESFET/HEMT devices and integrated circuits. Low-noise GaAs MESFETs with submicron gate lengths using optical and e-beam lithography have been reported which can operate at frequencies up to 60 GHz. Power GaAs FETs are capable of output powers of hundreds of milliwatts at Ku- and Ka-bands. More significantly, recent advances in monolithic integration of GaAs integrated circuits (ICs) have stimulated great interest in the applications of GaAs ICs for both analog and digital systems.

It is expected that with the advent of monolithic realizations, the complexity of the device and circuit design for GaAs ICs will increase significantly. Techniques common to the design of silicon ICs must be developed for GaAs ICs. We have developed an integrated approach involving both analytical and computer-aided design and synthesis techniques for the design of monolithic GaAs ICs. New and innovative circuit designs including

feedback and distributed amplifiers have been studied. Nonlinear circuit analysis programs are being developed for the analysis and design of monolithic GaAs MESFET/HEMT devices and circuits. An integral part of our technical approach is to verify our designs by the design and actual fabrication of prototype monolithic GaAs MESFET/HEMT circuits.

PROGRESS

General design theory for the GaAs MESFET and HEMT distributed amplifier has been developed. A CAD program to facilitate the design procedure was completed and tested. In keeping with the advances in HEMT research, we derived a complete I-V model to cover the entire range of operation, which includes the transconductance compression and subthreshold region. Excellent agreements are obtained between the measured and modeled I-V characteristics. A nonlinear HEMT model was developed based on the I-V model and incorporated into the nonlinear program, CADNON. After improvements in the GaAs MESFET modeling were made, we also employed CADNON to design and simulate a MESFET mixer, which was subsequently fabricated with success. Progress on the low-noise amplifiers using state-of-the-art quarter-micron HEMT's has been made. Excellent results were obtained for the design of low-noise HEMT amplifiers for millimeter-wave application. Progress of our research is summarized in the following subsections.

a) Design of Ultra-Wideband Distributed Amplifier Using GaAs MESFETs and HEMTs

The primary objective of this continuing research program is to develop the advanced and integrated analytical theory and computer aided design technique for distributed amplifiers using GaAs MESFETs and HEMTs. The distributed GaAs MESFET and HEMT amplifiers are directed toward system applications requiring multi-octave bandwidths.

Significant progress was made recently on the design of ultra-wideband amplifier using submicron gate length GaAs MESFETs and HEMTs.

We have developed the general design theory for monolithic GaAs MESFET and HEMT distributed amplifiers. The gate line is designed as a constant-K filter instead of a Chebyshev filter. At the same time the terminations of gate line and drain line have been redesigned. In addition, the program of computer aided design for distributed amplifier (DFETA) has been revised.

The revised DFETA can predict the gain performance of distributed amplifier exactly. The gain difference between the result calculated by DFETA and NODAL is less than 0.7 dB. Furthermore, the gain ripple of initial design by revised DFETA is less than ± 0.5 dB across the 2-26 GHz.

With state-of-the-art quarter micron HEMTs, a n=4 distributed amplifier covering 2-40 GHz with 7.5 dB gain and ± 0.5 dB gain variation has been designed. Quarter micron MESFETs distributed amplifiers covering 2-26 GHz with 7.5 dB gain and ± 0.35 dB gain variation have been designed. It is believed that this is the widest predicted bandwidth for amplifiers using either GaAs MESFETs or GaAlAs/GaAs HEMTs.

b) Nonlinear HEMT Modeling

We have recently developed an analytical and CAD model for HEMT I-V characteristics. This model was derived based upon the approximate solution of the electron transport equations in a GaAlAs/GaAs heterojunction and it includes velocity saturation effects, drain feedback effects, channel modulation effects, and a parasitic MESFET in the AlGaAs layer. Using this compact and flexible I-V model, we were able to simulate I-V characteristics of some state-of-the-art quarter-micrometer gate HEMT with excellent results, including GE #5415 0.25 x 150 micron HEMT, GE #5410 0.25 x 100 micron HEMT (see Figure 1), GE #226 0.25 x 150 micron HEMT, TRW #2241 0.3 x 80 micron HEMT, and TRW #2078 0.35 x 65 micron HEMT[1] (Figure 2). To verify the accuracy of the nonlinear HEMT model based on the I-V model, bias-dependent S-parameters of TRW #2241 HEMT was used to characterize the model and the S-parameters at different bias generated from the nonlinear model was then compared to the original S-parameters. The agreement between the measurement and model was excellent.

This model was incorporated into the nonlinear time domain program, CADNON, and will be used to simulate HEMT nonlinear circuits such as HEMT mixers, HEMT distributed amplifiers, and double heterojunction HEMT power amplifiers. These HEMT nonlinear circuit simulations will investigate the ultimate performance of HEMT under large-signal operation.

c) Design, Simulation, and Fabrication of Nonlinear MESFET Circuits

An X-band mixer using Raytheon #268 0.7 x 200 micron MESFET has been designed and simulated using the nonlinear time domain program, CADNON.

Simultaneously, a hybrid MIC X-band mixer using the same device was fabricated at Cornell. The simulation results when compared to measurements, show certain deviations. The possible causes for this disagreement were subsequently investigated. One possible reason for the discrepancy was the inaccuracy of the original MESFET model, which was then replaced by a more exact model derived from device physics. The more exact model included special features to model short channel effects and dynamic velocity overshoot. These two models were used to characterize a Rockwell 0.6 x 200 micron MESFET and generate bias-dependent S-parameters which were in turn compared with the measured S-parameters at different bias points. The results obtained from the new model show excellent agreement between experiment and model.

Design methods for MESFET power amplifiers and VCOs based on the new version of CADNON were also studied. The optimum load condition for a power amplifier can be determined from the perturbation analysis provided by CADNON. Based upon this information, the matching network for power amplifiers and embedding networks for oscillators can be designed using a linear circuit synthesis program such as CADSYN™. It is expected that the systematic design methods for specified nonlinear circuits will soon be completed.

d) Design of Low-Noise Broadband Amplifier Using GaAs MESFET and HEMT

Analytical and computer aided design methods for broadband Low-Noise Amplifiers (LNA) using GaAs MESFET have been extended to include the 0.25-0.5 micron gate-length HEMT devices. To investigate the superior noise property of HEMT at Ka band (26.5 GHz-40 GHz), a two-stage low-noise amplifier using GE #226 0.25 x 150 micron HEMT with minimum noise figure 1.8 GHz at 30 GHz has been designed with a predicted gain of 16 $\pm$ 0.4 dB and a maximum noise figure of 2.95 dB at the high frequency end. In comparison with the monolithic GaAs MESFET LNA for Ka band recently fabricated by Hughes, with an average noise figure of 7 dB and an associated gain of 14 dB,[2] this is believed to have the best performance for any solid-state device covering this frequency range. A GE 0.25 micron T-gate MESFET was also used to design a broadband amplifier for 20-40 GHz frequency range with a calculated gain of 4.9 $\pm$ 0.2 dB. These two LNA design examples show the effectiveness of our design method for millimeter-wave low noise amplifier. The 30-40 GHz low-noise HEMT amplifier will be fabricated in the near future.

DEGREES

1. Wang, Guan-wu, "An Analytical and Computer Aided Model for the High Electron Mobility Transistor", M.S. (August 1985).
2. Barker, Dean, "Design of Low Noise HEMT Amplifiers", M.Eng. (August 1985).

REFERENCES AND PUBLICATIONS

1. J.J. Berenz, "Low Noise High Electron Mobility Transistors", presented at 1984 IEEE Microwave and Millimeter Wave Monolithic Circuits Symposium, San Francisco, CA, May 1984.
2. L.C.T. Liu, private communication.

Fig. 1. Measured and Modeled DC Characteristics of GE #5410 HEMT

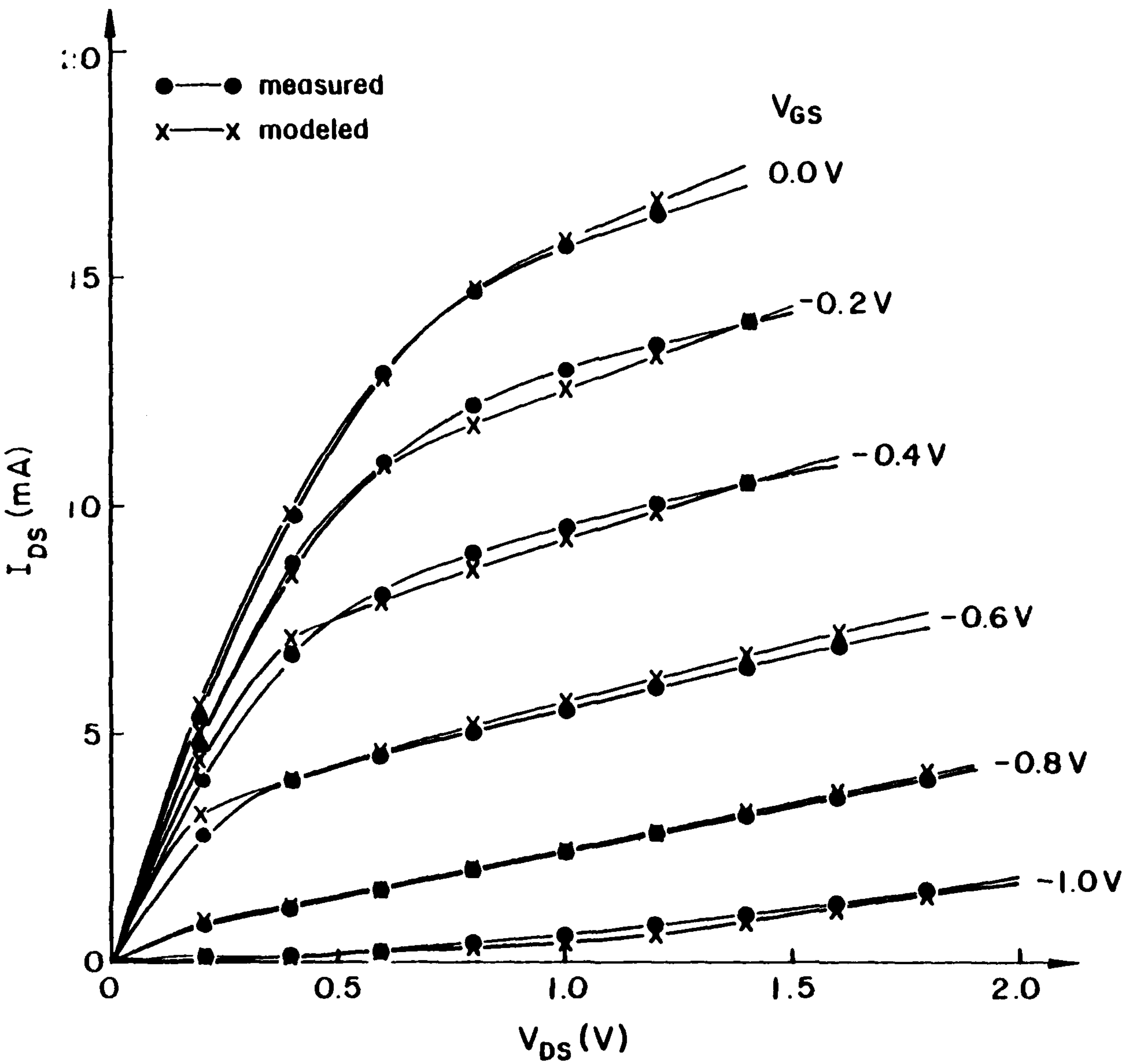
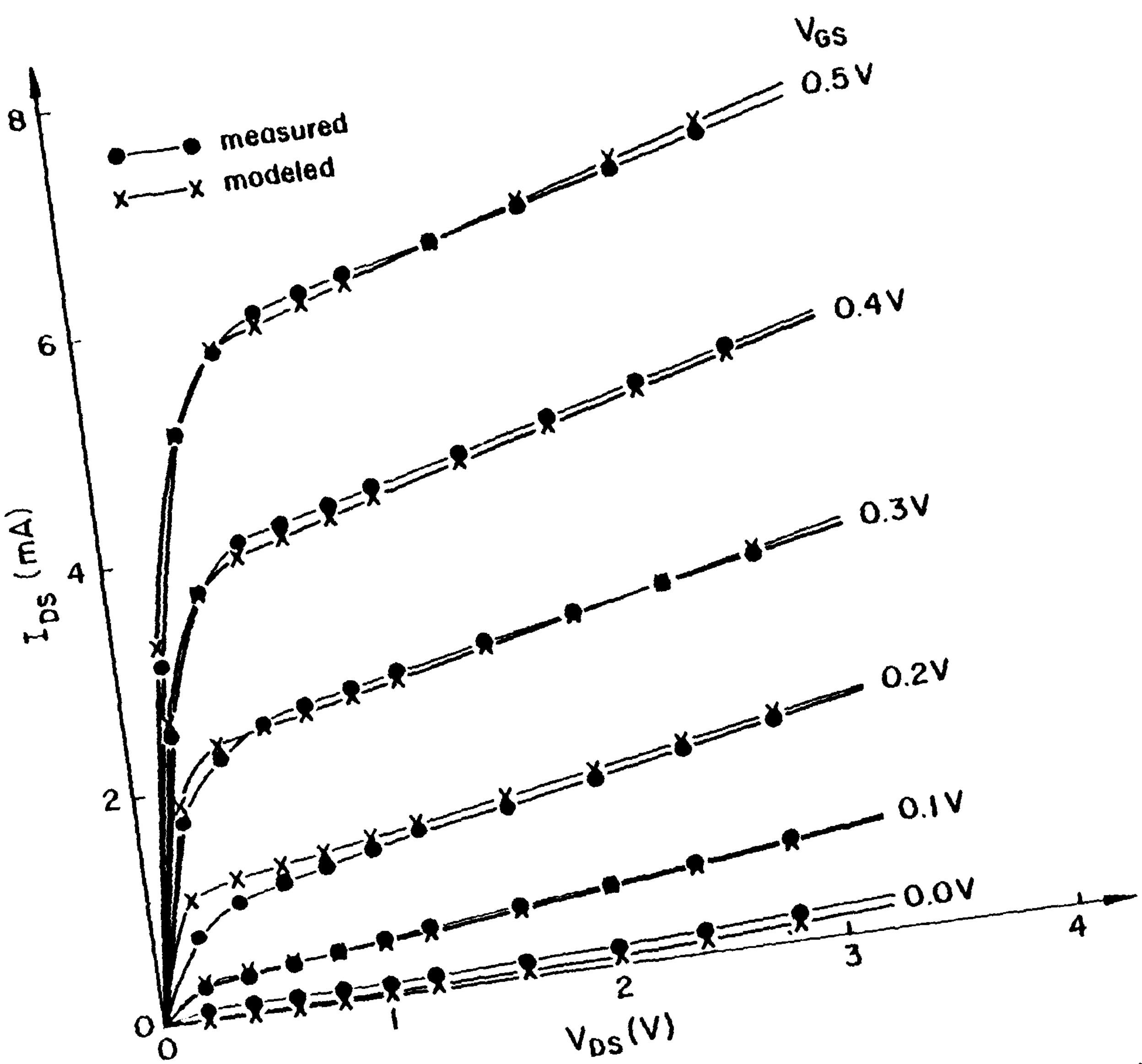


Fig. 2. Measured and Modeled DC Characteristics of TRW #2078 HEMT



TASK 9 WIDEBAND CIRCUITS AND SYSTEMS

H.J. Carlin

OBJECTIVE

Fundamental research on the application of gain bandwidth theory to design of wideband systems.

APPROACH

Basic network theory is used to obtain fundamental limitations, design methods, and practical models for microwave circuits and optical waveguide.

PROGRESS

A new and far-reaching fundamental result governing the optimum behavior of wideband amplifiers has been obtained. A comprehensive paper, "On Flat Gain with Frequency Dependent Terminations", by H.J. Carlin and Pier Civalleri, is to be published in IEE Trans. CAS, August 1985.

A new approach to modeling graded index optical guide with particular emphasis on dispersion analysis has been completed. A full paper will be presented at the IEEE MTT Symposium in St. Louis June 1985, "A New Approach to Dispersion Analysis in Graded Index Optical Fiber", by H.J. Carlin and Henry Zmuda.

DEGREES

Henry Zmuda, Ph.D., July 1984, "A New Approach to Dispersion Analysis in Graded Index Optical Fibers".

Christopher Near, M.S., January 1985, "Flat Gain Limitations in Complex Generator-Load Systems".

PUBLICATIONS

1. H. Carlin and P. Civalleri, "On Flat Gain With Frequency Dependant Terminations", to be published August 1985, IEE Trans.-CAS.
2. H. Carlin and H. Zmuda, "A New Approach to Dispersion Analysis in Graded Index Optical Fibers", Proc. IEEE MTT Symposium, St. Louis, MO, June 1985.
3. D.C. Youla, H.J. Carlin and B.S. Yarman, "Double Broadband Matching and

the Problem of Reciprocal Reactance 2-μ Port Cascade Decomposition", Intl. J. *Circuit Theory and Applications*, July 1984, V. 12, No. 3, pp. 269-281.

TASK 10 DEVICE SIMULATION AND CIRCUIT MODELING FOR III-V DEVICES IN THE BOUNDARY LIMITED HIGH FIELD TRANSPORT REGIME

J.P. Krusius

OBJECTIVE

The objective of this task is to explore stationary and transient hot carrier transport in semiconductor device structures, which are so small that carrier transport is significantly influenced by the device boundaries. The results of this study will aid understanding of hot carrier transport in the boundary limited domain, serve as guidelines for device design and optimization operating in this regime, and possibly lead to novel devices utilizing the special features of transport in this domain.

APPROACH

Stationary and transient hot carrier transport in the boundary limited domain will be studied theoretically via computer simulations based on statistical and Monte Carlo methods. Circuit implications will be explored using a newly developed tensor product splines based circuit modeling and simulation approach. Models and simulation results will be carefully correlated with experimental data whenever possible.

PROGRESS

During the first year of this program we have focused on carrier emitting and collecting boundaries. The simple one-dimensional n^+-n-n^+ ballistic GaAs diode has been selected as the model system because of its simplicity and the availability of measured data for model validation and correlation of results. Such n^+-n-n^+ diodes have previously been studied by a number of authors using transport methods based on drift and diffusion, method of moments, and Monte Carlo, but systematic device boundary investigations have to the best of our knowledge not been undertaken. We have selected the self-consistent Monte Carlo method for our transport studies, because it is the most flexible of all known methods for changing the underlying microscopic transport models. Within the self-consistent Monte Carlo method we can change mathematical descriptions of physical device boundaries conveniently without inducing a need to alter the mathematical solution algorithms.

A self-consistent Monte Carlo transport simulator has been developed

based on an early version obtained from Dr. P. Blakey (U. Arizona). Implemented new enhancements include for example non-parabolicity of dispersion relations and scattering rates, a correction for the finite size of the electron, and realistic models for three different physical boundaries. These are the periodic boundary, the thermal boundary, and the thermal-reflective boundary. Periodic boundaries would be found, e.g., in periodic multi-layer structures grown with MBE or MOCVD. Thermal boundaries constitute a simple model for the "ohmic" contact. The simplest model for an ideal metal-semiconductor contact is the thermal-reflective boundary. Carrier injection and ejection at periodic boundaries is periodic as well as the local electric field. At thermal boundaries carriers communicate with boundary temperature drifted Maxwellian distributions. Similarly at thermal-reflective boundaries carriers communicate with boundary temperature drifted Maxwellians but see in addition a finite reflection probability dependent on boundary characteristics.

Our self-consistent Monte Carlo approach has been correlated with experimental data for a periodically doped n^+-n-n^+ structures grown with MBE in Professor Eastman's group (M. Hollis, N. Dandekar, L.F. Eastman, M. Shur, D. Woodard and C. Wood, IEDM Tech. Digest, pp. 622-625, 1980). Periodic boundaries are appropriate for one period of the fabricated structure, but a model for the ohmic contacts at both ends of the periodic structure is needed in order to simulate the entire fabricated structure. Since a first order correction to account for the ohmic end contacts has been performed to the measured data, we have not attempted to model this effect. Simulated and measured current-voltage characteristics at 300 K show an excellent agreement over the full two decades of experimental data without any adjustable parameters in the Monte Carlo simulation approach (Figure 1). At 77 K our method predicts the correct behavior but shows consistently a slightly higher current density. This is attributed to the uncertainties associated with the ohmic end contacts.

n^+-n-n^+ GaAs diodes with a 250 nm long n-region have been studied. The length of the n^+ regions varied between 50 and 240 nm. The general conclusion on stationary and transient transport in these boundary limited GaAs structures is that device boundaries have a crucial effect on transport. Preliminary results have been reported in a paper given at the IEEE/Cornell High Speed Device Conference in July 1985.(1) Size effects have been studied by making the length of the n^+ regions approach electron scattering lengths in

GaAs. Devices with "short" emitting and collecting n^+ regions show a lower current, a lower drift velocity, a larger upper valley population, and higher electron temperature than "long" devices. Boundary type effects have been explored by comparing periodic, thermal, and thermal-reflective boundaries. Thermal boundaries exhibit higher currents, larger velocities, and less transfer into upper conduction band valleys than periodic boundaries. Thermal-reflective boundaries are qualitatively between the thermal and periodic cases with a strong dependence on the reflectivity. The transient response time of these "short" ballistic GaAs diodes is of the order of 1 ps independent of the device boundaries. This corresponds to an effective transit velocity of 2.4×10^7 cm/s across the n-region. The current in the initial transient regime shows an unexpected ringing effect, which is nearly independent of the device boundaries (Figure 2). Structure has been observed in the power spectrum of the current density in the frequency range from 200 GHz to 5 THz, which has tentatively been associated with plasma frequencies in the n-region.

DEGREES

None

PUBLICATIONS

1. A. Al-Omar and J.P. Krusius, "Boundary Effects on Stationary and Transient Characteristics of GaAs Device Structures", IEEE/Cornell 10th Biennal Conference on Advances in High Speed Semiconductor Devices and Circuits, July 29-31, 1985 (to be published).

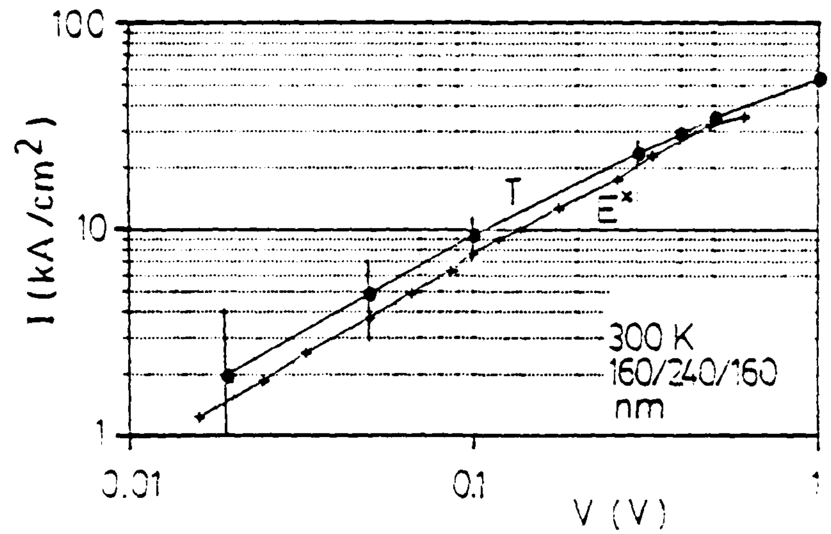


Fig. 1 Current density of ballistic n^+-n-n^+ GaAs diode as a function of applied voltage at 300 K. The Monte Carlo results are labeled with (T) and measured data with (E).

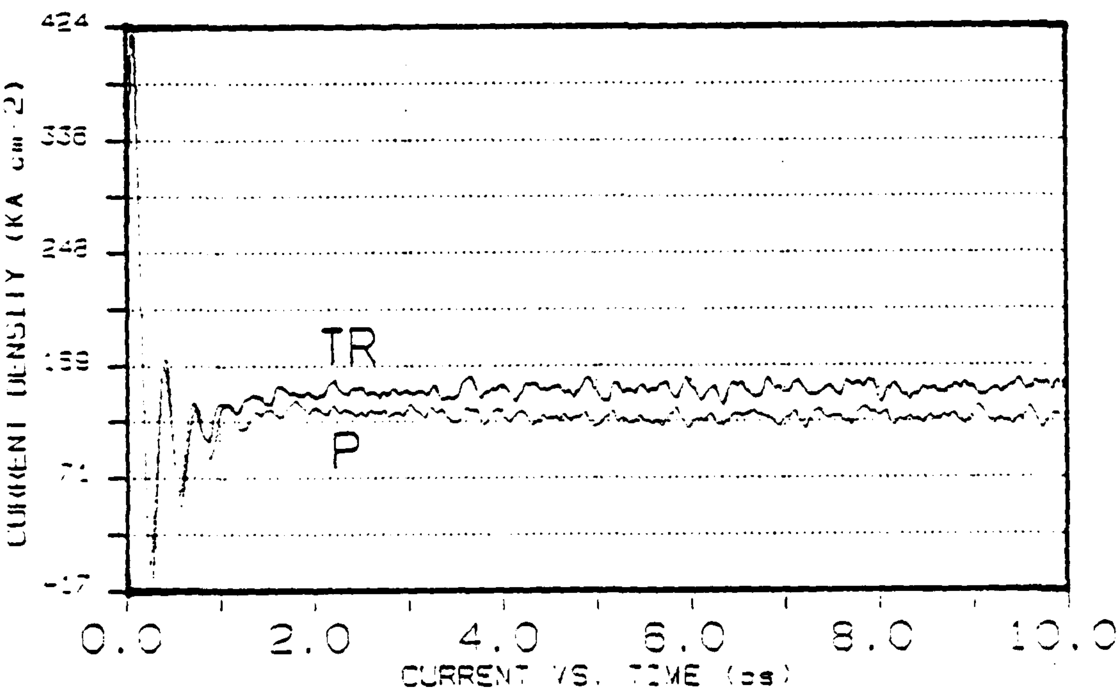


Fig. 2 Current density of ballistic n^+-n-n^+ GaAs diode as a function of time at 300 K. Results for periodic (P) and thermal-reflective (TR) boundaries are given. The initial state has zero applied bias and the final one 1 V.

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